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Review Article

Recent Clay Mineral Composition and Mineral Assemblages in the Sunda Shelf: A Review

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ABSTRACT

Sediment which presents at the bottom of the water column is the weathered product of sediments and mineral rock, mainly from drainage basins and from external inputs of surrounding marginal basins. Clay is weathered product mobilized from its source, where it consists of kaolinite, illite, smectite and chlorite. These compositions morphed into clay minerals, becoming a building block for the compaction of young sediment. Furthermore, fine-sized clay also leads to the accumulation and dissolution of clay minerals, with the presence of temperature and pressure, much like with chemical composition carried with it. The survey shows that the Sunda Shelf received its weathered sediments and minerals mainly via localized drainage basins or neighboring region as external inputs in its semi-marginal basins. The high rate of weathering which released large volume of weathered product and being channelled into the basin was due to the monsoons, affecting the surface plane of eroding sedimentary layers and mineral rocks. This literature survey revealed that information is still limited on clay minerals in Sunda Shelf, therefore further research is needed.

Keywords: Sunda shelf; Monsoon; Source; Transport; Mineral

INTRODUCTION

The Sunda shelf is one of semi-marginal basins with extensive occurrence of lacustrine sediments, incorporated in brackish lakes and freshwater during the mid-Cenozoic period [1]. The Sunda shelf extension is from Sumatra and West Java, through the Malay Basins, West Natuna, the Gulf of Thailand, the Nam Con Son and Coo Long Basins in Southern Vietnam (Figure 1), hosting lacustrine sediment and producing a major hydrocarbons output in the southern South China Sea (sSCS) [2]. The tectonic development Sunda Shelf has been poorly researched as the individual basins was appraised individually through isolation and examined independently within the nation's boundary [3]. Its hydrology consists of an ascending branch of the Walker circulation associated with deep convention zones. Water balance is affected by the monsoonal season and influenced by annual precipitation ranging from 1600 to 3500 mm/year [4].

In the Sunda shelf, the presence of the monsoon season may affect the total volume of sediment being transported to the shelf. The northeast monsoon which is present between November and March, brings north-easterly winds while winds in the opposite direction are present during the southwest monsoon from May to September [5]. During the monsoonal seasons, prevailing winds along the coastlines generate strong boundary currents, upwelling and downwelling along the coastlines. These may generate baroclinic instability and temperature difference on surface seawater [6]. The monsoonal seasons may consequently affect sediment transport towards the coast. During the course of sediment mobilization, the fine and coarse-sized grain are transported via friction, under the influence of moving fluids and the sediment grains which rest on bottom sediments. The sheer forces within the bottom boundary layer comprise small turbulent vortices that set up a moving stress-point between fluid and grains, which generates friction and affecting spatial and temporal distribution of sediment [7,8]. Paleoclimatic studies revealed that the Mekong

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River became a sedimentary source over the past 190 years, derived from the eastern Tibetan Plateau. Monsoon-controlled weathering and erosion occurred along the rivers leading to elevated clay mineral assemblage content (i.e., kaolinite, smectite, illite, and chlorite) [9]. On the other hand, the reconstruction of paleoclimate through chemical proxies (e.g., K/Rb, K/Al and Chemical Index of Alteration (CIA)) together with clay mineral assemblages have also shown that monsoonal influences are far more powerful on mobilization and distribution across shelf [10].

Several studies validate the hypothesis that periodic precipitation induced by the monsoon influence sediment loads during peak monsoonal seasons [11-15]. As precipitation occurs, it influences the rate of erosion onto terrestrial runoff before being mobilized through the river channel. On top of that, climatic forcing also affects the impact of chemical weathering onto the soil and sedimentary layers. Since a high level of precipitation occurs in the Kelantan and Pahang Rivers, soil and rock fragmentation by hydrolysis as form of chemical weathering is more efficient than physical weathering. The higher rate of hydrolysis intensity will eventually would lead to subtraction of concern mobile ion such as Na, K, Ca, Mg and Cr in the parent rocks [16]. In addition, the presence of tectonic forcing cannot be neglected as a main contributor to sediment accumulation on the Sunda shelf. Frequent earthquakes and volcanic eruptions can increase the erodibility of parent rocks, and has a history of affecting tectonic settings in the Mekong River and Red River. These rivers affected by the Tibetan Plateau; thus, they have a cold and humid climate at their headwaters, which significantly increase physical erosion compared to mere hydrolytic weathering process. The source of sediment in the Mekong and Red Rivers can therefore be attributed to the intensity of past tectonic activities, and tectonic-induced river incision, rather than being dominated by climatic forcing. The cumulative effect of weathering, the fracture and disintegration onto the parent rock would expose more surface area and leading to a higher chance that chemical and physical weathering occurs.

In essence, clay minerals refers to the group of <2 micron in size fractions of sediment which consist of hydrous aluminosilicates as its main constituent [17], associated with high degree of surface area and large cation exchange between media through the water column, thus having a high affinity towards organic and inorganic matters due to large surface areas. It is a significant indicator of marine pathways to drainage basins; where clay minerals are channelled through the river and sink in coastal shores in the same region [18]. Clay minerals are physically transformed from sedimentary rock, when continuous erosion leads to the weathering of sedimentary layers. This is the transformation of weathered rock to the clay mineral and it is at this point that its crystalline structure and ion arrangements are altered due to the physical erosion. These fractions of sediment, which are similar to the chemical and structural composition of the terrestrial crust, are derived from igneous and metamorphic rocks [19,20]. The elemental composition of most clay minerals originates from erosion or weathering, while others are from deeper waters. In the latter the removed elements from crustal layer were aluminium, silica, alkaline earth elements and iron which were formed at temperature less than 100°C and about to 450°C [21]. A common property of clay is its singular structural layer in a one-dimensional in shape within a nano-meter range, with a thickness at 0.7 nm [22].

The presence of clay minerals along the coastal through the weathering and dissolution of mineral rocks transported from drainage basins may contribute to the total accumulation that occurs in bottom seabed sediments. This is also because the dominant factor for clay production is determined by the periodic precipitation, wind and current speed. The objective of this paper is thus to review published studies of clay mineral as a potential indicator for changes in the marine environment, and to assess the use of clay minerals as an indicator for seasonal and temporal changes in the Sunda Shelf.

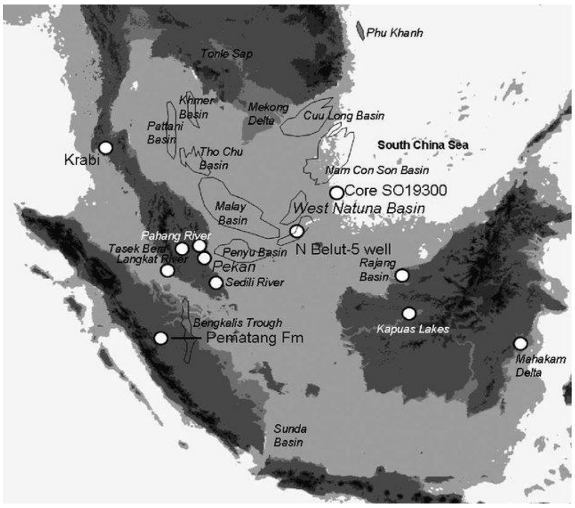

Figure 1: Location of Sunda shelf within the southern South China Sea (sSCS), data source [23].

COMPOSITION OF CLAY MINERALOGY

In order to establish sediment sources of aquatic environments, a study of clay mineral composition and surrounding environmental and climatic conditions is necessary. Clay minerals are a widely distributed component in different types of sediment; thus, it is important to locate the source, mode and magnitude of transport. Clay mineral sourced from drainage basins comprise of illite, chlorite, smectite and kaolinite. Studies reveal that changes in clay mineral composition due to weathering, mobilization, deposition and input on different tributaries may be revealed by the fluctuation of its composition [24]. Once a distance away from its source, clay minerals will sink and mix with mature seabed sediment. Clay assemblages also can be used as an indicator for reconstruction and movement within vertical core layers during the interglacial and glacial epochs [25]. The presence of variations in grain size and clay mineralogy are closely linked to changes in seasonality and monsoonality [26,27]. Periodic weathering and erosion at close proximity to the Antarctic ice sheet would lead to changes in clay mineral crystallinity and chemistry on the Antarctic continental shelf and would be of suitable use for studies in palaeoceanography and paleoclimatology.

Illite and chlorite

The visibility of illite is clear when feldspar, mica and other hydro-aluminosilicates are present, under the condition of weathering and removal of K+ at low temperature, combined with low alkaline environments. The range of illite crystallinity values is <0.4, 0.4-0.6, 0.6-0.8 and >0.8 which would determine its sources within the range. The low crystallinity value indicates that the land source region is weak in hydrolysis but poses a strong dry and cold weather condition [28]. Meanwhile, high chemical index of illite would suggest a strong hydrolysis as the illite is rich with Al, while low chemical index would indicate rich content of Fe-Mg within illite, due to physical weathering [29]. Many researchers use illite to identify mass transport and distribution due to hydrological, climatic and seasonal changes. Seasonal variation also leads to fluctuations of illite, for example, where the illite content in the Gulf of Thailand (GOT) was contributed by the outflow of the Mekong River and South China Sea hydrodynamics. However, the presence of the monsoonal season implies continuous upwelling and downwelling, with bottom resuspension mobilizing the illite from the upper GOT which located within river mouth region towards the southern GOT [30]. For sub-seafloor studies, illite properties are widely used to understand the origin and formation mechanism of clay minerals in the oligotrophic open ocean. Deep sea sediment excavation reveals that hydrothermal activities in seabed sediment alters the elemental composition of clay minerals as the Fe-rich basalt sediment is altered by persistent micro-environments of anoxic and hypoxic conditions [31]. Furthermore, terrigenous inputs from nearby sources also altered the total distribution of illite in marine environments.

Formed by a similar process in marine environments, chlorite and illite are formed via weak hydrolysis in surficial sediments or through the physical erosion of bedrock, usually within the cervices of surficial minerals and rocks [32]. Chlorite, micas-like clay is found in several variations of geological environments including sediment or hydrothermally altered mineral rocks within low grade metamorphic rocks. This chemical weathering results in detrital chlorite, and the product of this physical weathering predominates, especially continental inputs at high latitudes. In low temperature environments, it exhibits a minor difference in compositional diagenesis of low-grade metamorphic rocks towards higher grade of metamorphism which is found in sediment and mineral rocks. In sedimentary layers, chlorite in the diagenesis would tend to have a higher SI content, and lower Fe and Mg content, as well as an octahedral total higher than metamorphic chlorites, which is similar to the alumina content. In the process towards metamorphism from diagenesis, chlorite became less siliceous, while richer in Fe and Mg, as octahedral occupancy increases. Furthermore, the growth of this progressive chlorite is due to burial and heating, which then leads to a variety of grain coarsening process [33,34].

As for distribution in marine environments, chlorite was typically affected by climatic and seasonal variations, within clay and non-clay fractions. In marginal seas, the volume of chlorite decreases as distance increases offshore, providing an indication of the chlorite source from the drainage basin. In fluvial-derived samples, there is a high content of clay and coarse silt in the carbonate-free sediment along the coast. This is an indication of bimodal grain size distribution [35]. Chlorite abundance increases towards cold latitudinal zones, which are parallel to decreases of continental hydrolysis, and tends to concentrate towards the centre of marginal basins. In seasonal variations, cold and dry regions usually correspond to associations with chlorite, which reflect its abundance in marine environments. The amount of quartz, mica, minerals and directly removed from crystalline are more noticeable through constant weathering of rocks and sediments. Those higher volumes of chlorite along the Indochina Peninsular may have been contributed by the Red and Mekong Rivers [36]. Both rivers are subject to intense weathering that occurs within the upper streams of rivers that contain high amounts of igneous rocks, and amplified by seasonal monsoons. These types of weathering are caused by tectonic activities and river incision, accelerated by the presence of high precipitation and warm temperatures, leading to active weathering, and subsequently intensive silicate weathering that mobilizes towards the South China Sea. The strength of East Asian Summers during the Cenozoic era evolved from the past to the present, which can be detected through smectite/(illite/chlorite) variations. Strong monsoonal seasons aligned with solar radiation occurred during summer monsoons, leading to huge amount of clay mineral produced and transported in the bottom current along the Luzon arc [37].

Kaolinite

The existence of kaolinite in clay minerals is mainly from surface weathering and hydrothermal alteration where climatic conditions such as warmth and humidity on the surface of dense vegetation of interest activate the process. High erosion rates lead to higher acidity onto sedimentary layers thus further increasing erosion rates and leaching of eroded soils [38]. The primary compositions of these sedimentary layers are feldspar and mica; erosion and weathering thus results in kaolinite [29]. The intrusion of kaolinite into the river channel and a combination of physical factors would eventually affect the degree of weathering onto sedimentary layers and the mineralogy of mobilized weathered products in aquatic environments. The changes of K^+ ions in kaolinite-dominated clay minerals would play an important role for chemical weathering as it indicates land change responses and reflects total nutrient content related to storage within active sediment beds [39]. On the other hand, intrusion by kaolinite is also used as an indicator for seasonal variations. During intense precipitation and flooding season, suspended matter content in the water column increases in the river channel as erosion rates are magnified, acting upon sedimentary layers and mobilizing kaolinite content into the suspended matter [40].

Several studies have shown that kaolinite is an indicator for annual monsoonal records via weathering events. For instance, eroded soils in uplands classified as Oxisols of which the primary composition is kaolinite, followed by gibbsite, goethite and hematite exist in the terrestrial runoff due to climate forcing contributing to an increase in clay minerals within the water column [41]. The presence of organic matter related to kaolinite is highly correlated as both matters generate negative charges, thus organic matter has the potential to carry kaolinite throughout the river outflow towards the surrounding region [42]. As kaolinite becomes a major product as a result of weathering, the association of kaolinite with organic matter is predominant. Aluminous-hydrosilicate surfaces tend to bind with ions on leached surfaces under an anion exchange capacity that permits kaolinite association [43]. In the Bay of Bengal, a study stated that fluctuations of kaolinite content within the bay affect overall distribution, led by annual monsoonal seasons [44]. This leads to differences in total flux of clay being distributed along the bay, where higher amounts of clay are channeled from the Arabian Sea to the Bay of Bengal. It is even higher during the Northeast monsoon, but lower amounts of supply, sedimentation and overall clay content is disrupted during the Southwest monsoon. Kaolinite is used as a sea level indicator occurred during the Pleistocene period, where ancient Sunda shelf and Mekong River supplied a high contribution of detrital clay containing a large amount of kaolinite along the exposed ancient Sunda Shelf, towards the South China Sea. As sea level changed, several environmental changes and fluvial influences lead to the severe output of kaolinite towards the coastal [45].

Smectite

Through the alteration of chemical weathering, smectite is main swelling clay, which is prone to large volume change due to expansion properties exhibited in the clay; it thus performs well in shrink-swell capacity. The increment of K^+ sorption at surface temperatures increases smectite ability to swell. Meanwhile, the formation of smectite clay comes from shallow subsurface environments at the bottom seafloor, where alteration from illite-smectite mixed layer clays interchange under conditions of K^+ absorption [30]. During mobilization, smectite tends to be smaller in size, around 0.2 μm, which can be carried away, before settling. Flocculation is important in fractionating clay during the mobilization of clay from the drainage basin to the open ocean. It depends on the layer charge of particulates and the chemistry within which it suspended. Smectite has higher layer charges compared to other clay assemblages, leading to a different charging behaviour in clay. These layer charging properties are related to the swelling, a colloidal property and charge heterogenicity, including charge magnitude and charge localization. Moreover, layer charging properties also leads to the absorption of organic compounds on smectite surfaces [46]. The derivation of smectite during continental weathering is sourced from metamorphic rock and presented in granitic and diorite rocks, which is ideal for its growth. Clay that is mineral rich in Fe-Mg will produce trioctahedral smectite, during weathering [47]. On the other hand, preservation of smectite in the marine environment may be hindered by humidity and severity of weathering. Rapid and prolonged chemical weathering leads to the total dissolution of clay, which may prevent the preservation of smectite during burial or which may be present within surficial sediment [48].

USING CLAY MINERAL AS A POSSIBLE SEASONAL INDICATOR FOR THE SUNDA SHELF

Aside from studies on the abundance of clay minerals along the coast, other reports outline other uses of clay such as weathering properties and profile, climatic significance, pollution assessment, rock properties, sediment provenance, among others. Clay mineral is also used as a seasonal indicator within coastal region. According to the abundance of kaolinite during the Mesozoic period represents the humid and arid phases of paleo-weathering, leading to changes in sea level and continental precipitations [49].

On the other hand, an abundance of clay along the Yangtze River with large fluctuations of depositional environments was due to the impact of the summer monsoon. Their findings are in line with the weathering characteristics and the detrital clay component present in clay minerals. Furthermore, hydrodynamic changes aligned with the monsoonal season promotes the redistribution of clay minerals, thus causing changes to total clay mineral in the region.

The Sunda Shelf was affected by the northeast and southwest monsoons, which generate cyclonic and anti-cyclonic eddies while producing monsoonal tides and ebb. This leads to interchangeable phases between stratified and mixed water and affects the mixing of sediment within the coastal region [50,51]. Thus, with the possibility of clay mineral distribution and properties, it is possible for clay minerals to be used as a seasonal indicator in the Sunda Shelf.

The presence of clay minerals in the coastal without doubt is vital for number of assessments, from undisturbed origin until it becomes a weathered product and mobilizes towards the sinks (i.e., coastal areas, offshore). The semi-enclosed basin located on the Sunda Shelf coast is one of unique bathymetries within the South China Sea. These areas comprise a periodic monsoonal wind, with northeast winds from November until February and southwest winds from June to August.

During the northeast monsoon, surface current water flows from the north to the south, while reverse occurs in south-western monsoon (Figure 2).

This results in a large amount of mobilization and the reworking of surficial sediments and suspended particulates mainly originating from terrestrial mineral rocks and sedimentary layers, and subsequent deposition of clay minerals in the Sunda shelf [51].

Studies reveal that hydrological mechanisms under continuous process or elevated via the monsoon may contribute to the sediment fluctuation and clay mineral content, leading to mobilized clay minerals on several trajectories leading towards the coast [30,50]. Several rivers in the neighbouring region were chosen to illustrate clay mineral mobilization towards the Sunda Shelf.

Area	Suspended Sediment discharge [mt/yr]	Smectite [%]	Illite [%]	Chlorite [%]	Kaolinite [%]	Source
Kelantan River	13.9	0	16	1	83	[52]
Pahang River	20.4	1	17	1	81	[52]
Chao Phraya River	11	6	41	33	20	[30]
Mekong River	160	11	35	26	28	[36]
Red River	130	7	44	24	26	[36]

Table 1: The value of contributed clay mineral assemblages surrounding the Sunda shelf.

The data obtained suggests that the source of sediment mobilized towards the Sunda shelf is continuous and elevated during the monsoonal season, leading to higher discharge volumes.

For instance, accelerated weathering during the monsoonal season from mountainous ranges from Titiwangsa, situated in the Central belts within the Sunda shelf [53].

The Sunda shelf is divided into three belts, the Western Belt, Central Belt and Eastern Belt. The Titiwangsa ranges is layered between these three belts, leading to a high output of igneous rocks and thus affecting the total output towards the coastal. Meanwhile the Chao Phraya and Mekong Rivers obtain weathered products largely from mountainous Tibet.

It stated that weathered product form the mountainous Tibet are largely produced the chemical weathering, while dilution along the riverbanks of both rivers may promotes as minor contribution to the coastal [52].

The long pathways may permit clay content fluctuations towards the coastal. During continuous weathering within the mountain ranges, weathering is accelerated by continuous precipitations and is transported along river channels leading to dilution, diffusion and mobilization within the river channel.

Following mobilization within the Titiwangsa and Tibet mountainous ranges, most of the weathered product is mobilized far from its origin leading to accumulated products within the coastal region.

In addition, the presence of tides and water current, the process of dilution, desorption resuspension and diffusion may affect the volume of weathered product being carried out to the coast.

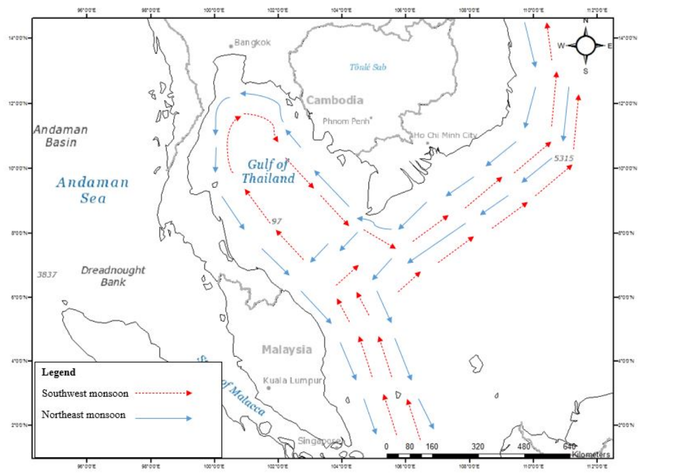

Figure 2: Surface current flows in the Southern South China Sea during the winter northeast monsoon, and surface current flows during the summer southwest monsoon. Data source [54].

With the presence of the monsoonal season, weathered products mobilize towards the drainage basins, leading to coastal as its final deposition site. Circulation driven by the monsoonal season also promotes resuspension processes along the coast, leading to fluctuating clay distribution along the Sunda shelf. Tidal dominance within the shelf area may contribute to sediment transport and distribution resulting in total sediment flux being transported to the Sunda shelf via monsoonal-driven circulation processes [55]. As sediment transportation occurs, the majority of the mobilized weathered product is in the clayey form due to high surface areas and the highest affinity for mobilized attachments, thus becoming a major carrier. This may lead to differences in volume of clay assemblages where adjacent coastal areas become a major sink for these weathered products. Since the Sunda Shelf become a major sink in the Southern South China Seas (sSCS), the fluvial discharge from neighbouring regions may contribute to the total volume of suspended clay which is present in the coastal shelf. This suggests possible input from the cross-shelf, thus, influencing possible distribution during pre and post-monsoonal seasons [54].

As adjacent coasts becoming a major sink for weathered products, major clay assemblages (i.e., kaolinite, smectite, illite and chlorite) may be permanently affected when under the influence of pre- and post-monsoonal seasons. Several weathering processes alongside mobilization leads to a continuous supply of weathering product to the coast. As igneous rock populates the Southeast Asian region and its mountain ranges, the following changes may support the hypothesis of clay being a monsoonal indicator for the Sunda shelf. Basically, clay supply is considered a major output via nearby drainage basins, of which warm and humid climatic conditions on dense vegetation is necessary to activate the weathering. Along the river, the predominance of kaolinite via clay fractions is well known as the weathering of igneous or metamorphic rocks and sedimentary kaolin deposits involved in sedimentary clay-rich rocks. The major precipitation that occurs in the Kelantan and Pahang Rivers during pre- and post-monsoonal season may alter kaolin deposits and sedimentary layers present in terrestrial regions and subsequently flowing through the river channel. According to [52], kaolinite represents intensive hydrolysis under a warm and humid climate, causing the parent rock to be leached in alkali and alkaline element. A warm and humid climate is common in Sunda shelf, under both northeast and southwest monsoons [56]. In combination with the high content of kaolinite within the Sunda shelf due to the presence of metamorphic rocks, this can lead to stability and sufficient time for kaolinite to be weathered and mobilize freely within the river channels.

The present of smectite as one of the clay assemblages is well known as a component of weathered minerals in igneous rock [20]. Since smectite is capable of absorbing most ions and metalloids, it is apparent that smectite become the main carrier for mobilization due to its affinity to other ions and metalloids with high absorption and desorption rates [57]. Looking at clay as an indicator for monsoonal changes, it also permits changes in geochemical concentration where continuous weathering is affected by changes in temperature, pressure and the rate of precipitation within the weathering regions [58]. Nevertheless, a low smectite volume as intermediate-basic rocks are scarce in the Sunda shelf highlands [Peninsular Malaysia] one of the primary rocks for smectite production during weathering, leading to lower amounts of mobilized clay in river channel towards the coast [58]. As shown in Table 1, a high amount of smectite was present in the Chao Phraya and Mekong Rivers due to the Himalayan-Tibetan ranges being a major supply of smectite towards the coast [59]. This high volume of smectite is similar to findings in several studies conforming the high volume produced by the Mekong and Chao Phraya Rivers, eventually supplying and sinking to the sSCS coast [36,60-62]. Thus, monsoonal seasons have a large impact on smectite distribution within the coast as the accelerated monsoonal winds and tides may transport a large amount of smectite towards the Sunda shelf.

Although terrestrial sedimentary layers are susceptible to weathering, illite is known for not weathering easily in warm and humid climates [63]. Regional mobilization of illite, mainly present in the coastal area of Indochina may contribute towards the increment of illite in the surrounding Sunda shelf [64]. Following periodic monsoonal seasons, a mixed supply from Indochina from irregular discharge [landslide, flood and typhoon] may lead to the coasts being saturated with illite, as corroborated in other studies [9,32,65,66]. Thus, monsoonal seasons have a large impact on smectite distribution within the Sunda shelf as the accelerated monsoonal wind and tides may transport a large amount of clay assemblages towards the shelf. Higher chlorite volumes were found in the Rajang Basin due to active tectonic settings in North Borneo since the Mesozoic period, and especially the rapid uplift during the Oligocene-Miocene era. The combination of monsoonal seasons and an active tectonic setting has resulted in extremely strong physical erosion. Even as weak hydrolysis acted on parent rocks, intense seasonal precipitation can increase physical erosion to form clay mineral assemblages comprising largely of primary illite and chlorite. The Rajang Basin thus contributes more illite and chlorite content towards the sSCS.

CONCLUSION

In this paper, sediments and the minerals were subjected to weathering, which leads to the production of clay during mobilization. Several sources of clay were generated through natural input, with flooding, wet and dry deposition and weathering. Anthropogenic inputs also play a role in increasing total clay output towards the coastal, especially with increasing deforestation and industrialization. With regard to mobilization, monsoonal inputs becoming a factor for erosivity. Eroded product contains kaolinite, smectite, illite and chlorite, through the combination of abrasion on planar surfaces, hydration and oxidation, leading to an increase of trace elements, nutrients and mineralogy in the sinks. This also can be traced back to activities from adjacent source. Thus, more studies are needed on clay minerals, especially on its composition (kaolinite, smectite, illite and chlorite), which linked to its myriad sources in the Sunda shelf.

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